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**Intermountain
Forest and Range
Experiment Station**

Research Paper
INT-276

July 1981

Why Windspeeds Increase on High Mountain Slopes at Night

Robert G. Baughman

RESEARCH SUMMARY

Research findings support the contention that the well-documented increase of windspeed on high mountain slopes at night is due to the occurrence of a low-level jet wind. Various aspects of the meteorological situation most likely to produce these nocturnal mountain winds are discussed. An established jet-wind theory (Blackadar 1957) can be used to predict the strength of these mountain winds during the course of an entire night. An example is given of a low-level jet wind that produced strong winds on a ridgetop fire at night.

The purpose of this report is to explain the windspeed increase on mountain slopes at night. Additional work is required to determine such things as the frequency of the winds, the area affected, seasonal variation, and the effect on fire behavior. Also, additional studies are needed to develop the type of procedures required to forecast these nocturnal mountain winds.

THE AUTHOR

ROBERT G. BAUGHMAN was introduced to meteorology while serving as an air-crewman with the U.S. Navy Air Corps during World War II. He later received degrees in meteorology and climatology from the University of Washington (B.S. 1954, M.S. 1957). During the period of 1954 through 1958, he was engaged in arctic and cold regions research while with the U.S. Army Corps of Engineers. In 1958, Baughman joined the USDA Forest Service as a research meteorologist, with responsibility for research on fire-setting lightning storms, weather modification, and forest meteorology. Currently he is a member of the Fire Behavior research work unit at the Northern Forest Fire Laboratory in Missoula, Mont.

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INTRODUCTION

The diurnal change of wind velocity on high mountain slopes and ridges differs from that of lower levels. Usually, the wind velocity increases on the higher slopes and may reach a maximum value at night and a minimum during the daytime (Yoshino 1975). The occurrence of these stronger winds blowing on a ridgetop fire at night can prove very frustrating to fire control crews who often count on a nighttime lull in fire activity. Such winds could not only fan a fire, but could also carry firebrands much further than expected and widely disperse smoke and pollution.

The existence of this particular weather phenomenon in mountainous areas has been reported in literature over the past 40 years. Gisborne (1941) declared that on mountaintops the maximum wind velocity is often reached during the night. Barrows (1951) states, "On the upper slopes of the mountains the peak velocities may be reached much later in the day, and frequently at night." Byram (1954) related a low-level jet current to extreme fire behavior. Several of his case-history fires were located in mountainous country. According to Schroeder and Buck (1970), low-level jet winds have not been studied in rough mountain topography; however, the higher peaks and ridges above lowland night inversions may occasionally be subjected to them. Brown and Davis (1973) say, "While low-level surface winds are generally weakest at night, the reverse is noted on mountain ridges; that is, ridge winds tend to be stronger at night and weaker during the daytime."

The cause of these nocturnal mountain winds has not been fully explained. A few researchers have related the cause to the occurrence of low-level jet winds, but details are not given (Schroeder and Buck 1970; Lee[1]). A more complete explanation of the windspeed increase on high mountain slopes at night is given here. The key to the explanation is the common occurrence of nocturnal temperature inversions in mountain valleys. The top of the inversion layer provides a smooth fluid interface that enhances the formation of a low-level jet (Hoecker 1965). The mountain slopes and ridges that extend above the surface inversions are exposed to the jet wind and are thus subject to strong surface winds.

Included in the explanation given here is a brief discussion of a particular low-level jet wind theory (by Blackadar 1957) that can be used to predict the strength of these mountain winds during the course of an entire night. Also discussed is the type of synoptic situation most likely to produce these winds. Finally, shown here is an example of a low-level jet wind that produced strong winds on a ridgetop fire at night.

The primary purpose of this report is to offer a reason for stronger windspeeds on high mountain slopes at night. Additional work is required to describe the extent of the problem, at least in terms of fire behavior. This requires studies to determine: the frequency of these winds, the area affected, the season variation, and the effect on fire behavior. Also, additional studies are needed to develop the type of procedures required to forecast these nocturnal mountain winds.

[1]Lee, Glenn M. 1959. Observations of ridge-top winds in northeastern Oregon. Unpubl. rep. 3 p. On file at Northern Forest Fire Laboratory, Missoula, Mont.

BACKGROUND INFORMATION

Several low-level jet-wind mechanisms have been proposed (Blackadar 1957; Wexler 1961; Lettau 1967), but only one of these applies over any continental surface, whether it be level or mountainous. According to Blackadar (1957), the low-level wind maxima is best developed on the Great Plains at night; however, examples may be found almost anywhere in the United States during any season of the year. The phenomenon results from rapid relaxation of friction drag at about the time of sunset. During the day, convective mixing produces a relatively deep friction layer above the earth's surface. Air movement in this layer is retarded by frictional drag. At night, thermal convection ceases and the earth's friction layer decreases in vertical extent. Air just above the nighttime friction layer, free of the daytime frictional drag, responds by accelerating under the influence of the unbalanced Coriolis and pressure-gradient forces. During the course of the night the air accelerates beyond the geostrophic value (supergeostrophic) before decreasing again.

The formation of a nocturnal temperature inversion will further damp out vertical mixing and enhance the buildup of a low-level jet wind. It has been observed that temperature inversions occur in mountainous regions at all times of the year. For example, detailed measurements by Hayes (1941) revealed that nocturnal inversions are common during the summer months in the Priest River Valley of northern Idaho. Schroeder and Buck (1970) point out that inversion layers are more common and more intense in mountain valleys than over flat areas and that the height of the inversions is usually below the main ridges. The land surface above the inversions is subject to increased windspeeds.

BLACKADAR JET-WIND THEORY

Blackadar (1957) derived a theory that explained the low-level jet in terms of a mechanism that can produce a diurnal variation of wind velocity in the boundary layer over any continental land surface. He assumed the motion just above the temperature inversion layer is completely horizontal and frictionless, and the horizontal pressure gradient is constant with time. An equation was derived that describes the deviation from the geostrophic wind. The solution is

$$W = W_o\, e^{-ift} \qquad (1)$$

where W is the deviation from the geostrophic wind at time t and W_o represents the deviation at an initial time, which may be taken to be the time of sunset (fig. 1). The letter i is the imaginary unit of a complex number and f is the Coriolis parameter.

The flow is one of inertia oscillation. After release of friction, the flow of air accelerates under the unbalanced Coriolis and pressure-gradient forces. The deviation from the geostrophic wind remains constant in magnitude, but is driven constantly to the right by the Coriolis force during the night at a constant angular speed of f radians per second. If continued, the motion would perform a complete revolution. The circle of inertia marks the loci of the end positions of the wind vector as a function of time. The period of a complete revolution is one-half pendulum day (Hess 1959). A supergeostrophic maximum windspeed is reached about $t = \pi/f$ hours after sunset (about 8.5 hours at 45° latitude).

Blackadar's theory permits prediction of the wind distribution during the entire night from initial conditions. Field observations show that the locus of points (head of the wind arrows) actually stretches out into an elliptical form instead of a perfect circle as given by figure 1 (Buajitti and Blackadar 1957). The elliptical path results from gradual relaxation of friction.

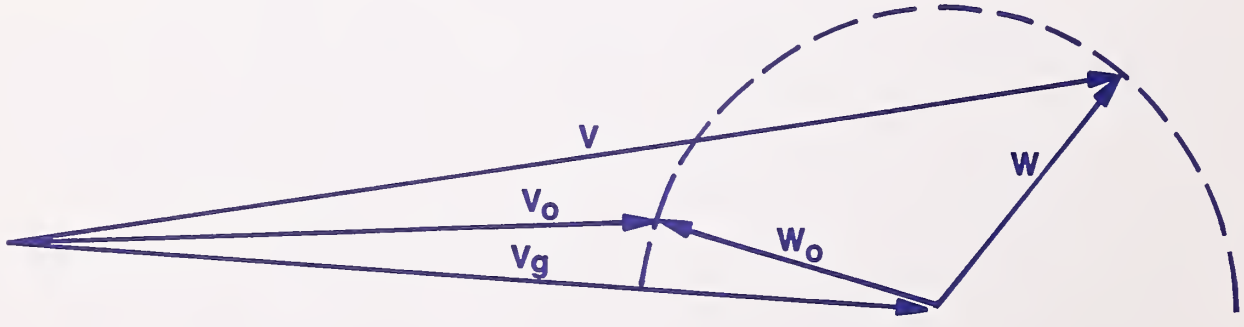

Figure 1.—Development of supergeostrophic winds in the low-level jet (after Blackadar 1957). V_g is the geostrophic wind, V_o the initial wind, and V the true wind. W and W_o are defined in equation 1.

SYNOPTIC CONSIDERATIONS OF THE LOW-LEVEL JET

The sharpness of the wind maximum tends to be enhanced when the geostrophic wind decreases with height (Blackadar 1957). Following this observation, it is useful to examine an expression describing the change of the geostrophic wind with height. Consider the following analysis:

$$\frac{\partial p}{\partial z} = -\rho g \text{ (hydrostatic eq.)} \quad (2)$$

$$p = \rho RT \text{ (eq. of state)} \quad (3)$$

$$fV_g = -\frac{1}{\rho}\frac{\partial p}{\partial n} \text{ (geostrophic wind)} \quad (4)$$

where n is normal to and increases to the left of the velocity vector. Now eliminate ρ using eqs. (2) and (3), then:

$$\frac{1}{p}\frac{\partial p}{\partial z} = -\frac{g}{RT}$$

and then differentiate with respect to n

$$\frac{\partial}{\partial n}\left(\frac{1}{p}\frac{\partial p}{\partial z}\right) = \frac{g}{RT^2}\frac{\partial T}{\partial n} \quad (5)$$

Now write (4) as

$$\frac{1}{p}\frac{\partial p}{\partial n} = -\frac{fV_g}{RT}$$

and differentiate with respect to z

$$\frac{\partial}{\partial z}\left(\frac{1}{p}\frac{\partial p}{\partial n}\right) = \frac{fV_g}{RT^2}\frac{\partial T}{\partial z} - \frac{f}{RT}\frac{\partial V_g}{\partial z} \quad (6)$$

Since

$$\frac{\partial}{\partial n}\left(\frac{1}{p}\frac{\partial p}{\partial z}\right) = \frac{\partial}{\partial z}\left(\frac{1}{p}\frac{\partial p}{\partial n}\right)$$

then

$$\frac{fV_g}{RT^2}\frac{\partial T}{\partial z} - \frac{f}{RT}\frac{\partial V_g}{\partial z} = \frac{g}{RT^2}\frac{\partial T}{\partial n}$$

or

$$\frac{\partial V_g}{\partial z} = \frac{V_g}{T}\frac{\partial T}{\partial z} - \frac{g}{fT}\frac{\partial T}{\partial n} \quad (7)$$

The first term on the right of (7) is less than one-tenth of the second term. Neglecting this term:

$$\frac{\partial V_g}{\partial z} \simeq -\frac{g}{fT}\frac{\partial T}{\partial n} \quad (8)$$

which is a form of the thermal wind equation. According to equation 8, for the geostrophic wind to decrease with height above the jet maximum, the temperature to the left of the geostrophic wind must increase along n. Since low pressure is also to the left of the geostrophic wind this requires the presence of a warm low-pressure system.

Observations have shown this to be the case. Means (1952) found that, for the central United States, supergeostrophic winds are found in low-level jets where isotherms are approximately parallel to the streamlines with warmer air toward lower pressure. Hoecker (1965) noted the meteorological conditions during three southerly low-level jet systems included warm low-pressure area to the west (left) of the jet. Also he noted that the occurrence of a surface nocturnal inversion allows greater increased low-level vertical shear, which favors a higher jet speed for a given initial pressure gradient.

It is important to note that the thermal wind component has a direction parallel to the isotherms of the mean temperature of the layer considered with high temperature to the right. This is just opposite of the situation for a decrease of the geostrophic wind with height. Therefore, in this case, the thermal wind opposes the geostrophic wind. This was proposed in a theoretical hodograph developed by Blackadar and found in observations by Hoecker (1965). In two cases Hoecker found that the thermal wind vector almost directly opposed the sea level geostrophic wind. Also, he states, "The opposition of the sea level geostrophic and thermal wind vectors is indicative of a warm low-pressure system in the region and since a warm low pressure system is shallow, the geostrophic wind (as well as the real wind) should decrease with height." Hoecker suggests (based on his observation in the Oklahoma-Texas area) that "if an adverse thermal wind exists at about 1800 CST along with a southerly low-level flow, and if the adverse thermal wind can be forecast to persist during the following hours of darkness, the boundary-layer jet system (speed maximum at about 300 m above the ground),. . .can be expected to occur that night."

The jet wind does not necessarily have to occur at night. According to Blackadar (1957), the jetlike profile may occur even in the daytime and conversely, the jet effect may not occur at all during the night if the geostrophic wind increases too rapidly upward. Rider (1966) observed low-level jet winds at the White Sands Missile Range. He observed that, although the low-level jet was predominantly a nocturnal phenomenon, with the nose of the jet near the height of the nocturnal temperature inversion, significant low-level wind maxima are sometimes found in the daytime. Also, there were a few cases where a jet formed even though lapse conditions prevailed, and there were cases where a temperature inversion developed during the night but a significant low-level jet was not evident.

REPORTED JET-WIND OBSERVATIONS

Measurements made at Silver Hill, Md., by Gifford (1952) provided clear evidence that windspeeds at the level of the jet maximum (2,000 ft [610 m]) are considerably supergeostrophic. Similar conclusions may be drawn from the analysis of low-level wind maxima at 0300 local time at San Antonio, Tex. (Blackadar 1957). Some other early measurements made at O'Neil, Nebr., during a 6-week period in the fall of 1953, illustrated several well-developed low-altitude wind jets (Barad 1961). Barad asks, "How did so strong and distinct a pattern go so long undetected?" The answer is simply that standard observation techniques were inadequate to find it. Observations on a 1,400-ft (427-m) tower near Dallas, Tex., clearly showed the

existence of a low-level wind maximum during periods of temperature inversions (Thuillier and Lappe 1964).

Windspeed observations on high mountain slopes at night are not common. Nevertheless, Lee[1] noted ridgetop windspeeds were considerably stronger at 0300 P.s.t. than at 0800 P.s.t. in the Blue Mountains of northeastern Oregon. Wind profile measurements at Burns, Oreg., indicated a definite wind maximum at low levels during the night. Perhaps Lee was the first to refer to Blackadar's theory as an explanation of the observed strong mountain winds. And as noted before, Rider (1966) also observed low-level jet winds over mountainous terrain.

The recorded occurrence of low-level windspeed maxima in conjunction with a forest fire in mountain areas is apparently quite rare. Byram (1954) observed jet currents over fires in South Dakota and California. Small (1957) reports that careful examination of the Boise Weather Bureau records indicates the presence of a low-level jet point on each day of significant spread by the Robie Creek Fire of 1955 in southern Idaho. Also, Finklin (1973) discussed the possibility of a low-level jet wind affecting the major run of the Sundance Fire in northern Idaho in the fall of 1967.

SUNDANCE FIRE - LOW-LEVEL JET

There is strong evidence that a low-level jet wind also occurred 3 days before the major run of the Sundance Fire. An account of this earlier outbreak of the fire is given by Anderson (1968).

> Late in the evening of August 29, at 2220, Priest Lake Timber Protective Association Headquarters near Coolin, Idaho, received word the fire had jumped the line and was out of control. Men and equipment were evacuated to headquarters. The fire was observed rolling down the hill in the Lee Creek drainage. a northeast wind had prevailed throughout the day and it is assumed this wind, coupled with the normal nighttime downslope currents, resulted in a wind-driven fire moving downslope. Information available from observers indicated the winds were 20-25 mi/h on the fire, but there was calm at Cavanaugh Bay near Coolin. The ground and crown fires were observed to move as a single front, with spotting up to one-half mile ahead. The main advance took place between 2230, August 29, and 0200, August 30, which would give an average rate of spread of 0.80 mi/h.

There was no direct measurement of a surface inversion in the area, but there is little doubt that one occurred during the night of August 29, because the region was under the influence of a high-pressure ridge at the time (Finklin 1973). Also, in an unpublished report (G. A. Verdall, letter in files at the Northern Forest Fire Laboratory, dated Oct. 5, 1967), it was reported, "Cooler air had filled the valley bottom; therefore there was no wind at our location (Cavanaugh Bay)." Verdal went on to say, "What made the fire behavior seem unusual to me was that I was standing in calm air watching a wind driven fire." Also he said, "To me, the fire behavior witnessed at that time was more spectacular and more unexpected than the major run the fire made on September 1."

The fire burned from the top of Sundance Mountain (6,000 ft [1 830 m] m.s.l.) down to about the 4,000 ft (1 220 m) level (fig. 2). The windspeed was quite strong on the ridgetop while it was calm some 2 miles away at Cavanaugh Bay (2,500 ft [762 m] m.s.l.). According to the low-level jet-wind theory, this is not an unexpected result, because the ridge was exposed to the jet wind while Cavanaugh Bay was protected by the temperature inversion layer. Upper air information was not available for the fire site, but it was available for Spokane, Wash., about 50 miles (80 km) southwest of the fire. The data clearly show the presence of a low-level jet wind during this early fire outbreak (fig. 3).

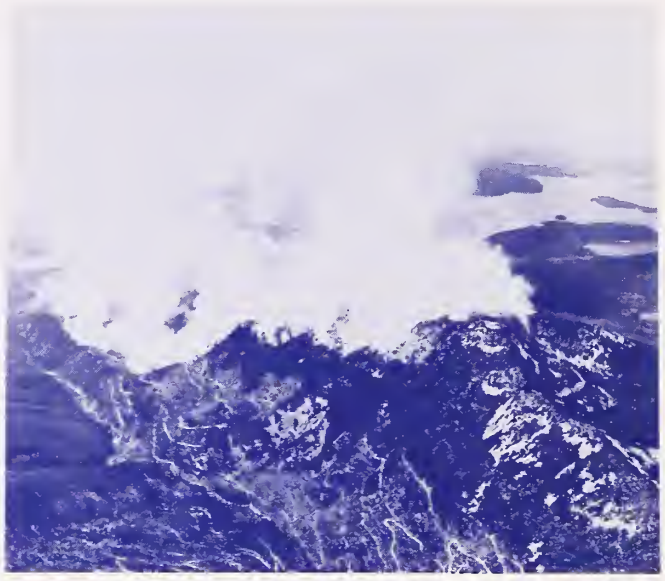

Figure 2.—Sundance Mountain after the fire's night run on August 29, 1967.

The windspeed on the night of August 29-30 was from the east to northeast reaching 15 to 20 mi/h (6.7 to 8.9 m/s) at a nearby mountaintop fire-weather station (Lunch Peak). "These winds were associated with a cool surface high to the northeast, moving southeastward across Alberta and Saskatchewan" (Finklin 1973). The surface map of 0600Z, August 30 (2200 P.s.t., August 29, time of the fire outbreak) revealed the presence of the cold high-pressure system mentioned by Finklin and a small, warm low-pressure system to the southwest of the fire site over eastern Washington. This was just the type of synoptic situation required to produce an enhanced low-level jet wind; that is, opposing thermal and geostrophic wind components. The windspeed profile at 1600 on August 29 (fig. 3) was nearly constant with height up to 8,000 ft (2 440 m). At 2200 (August 29), the time of the fire outbreak, the jet was well formed, reaching a velocity of 20 knots (east wind at 23 mi/h [10 m/s]), at an elevation of 5,000 ft (1 525 m). The jet was still present early the next morning as shown by the 0400 sounding of August 30; still east at 20 knots (10 m/s). Strong winds continued at Lunch Peak during the morning hours decreasing to 10 to 12 mi/h (4.5 to 5.4 m/s) at 1400. The Spokane data for 1100 (August 30) is missing, but the

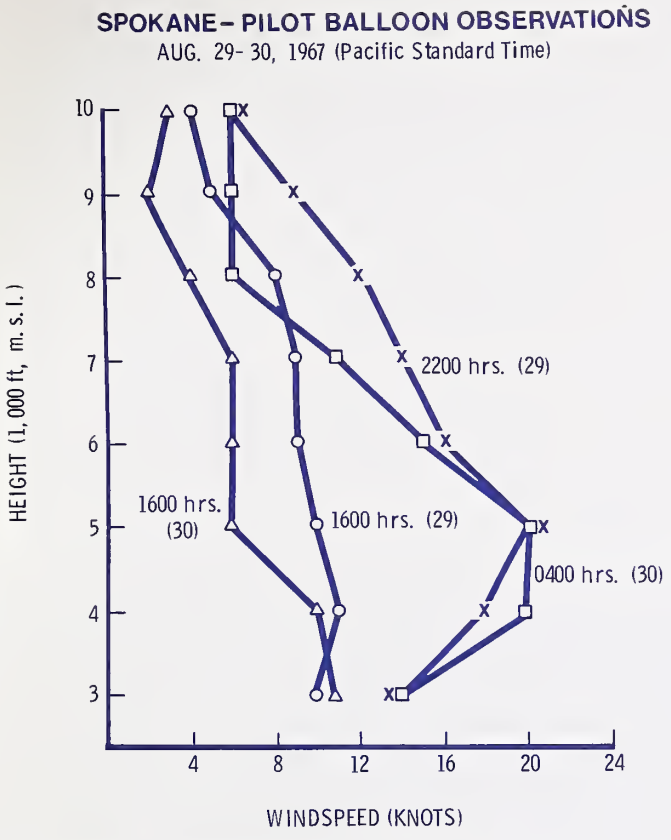

Figure 3.—The Sundance Fire low-level jet wind.

afternoon sounding (1600) showed the wind had died down before extreme high windspeeds drove the fire northeast during the major run in early September.

SUMMARY

It is well documented that windspeeds often increase and may reach maximum values on high mountain slopes during the nighttime hours. Evidence given here, including published information, supports the contention that this weather phenomenon is due to a low-level jet wind. Blackadar's low-level jet theory (1957) can be used to help predict the wind velocity during the night from initial conditions. The jet wind is enhanced by the formation of a surface temperature inversion and the occurrence of a thermal wind component that opposes the geostrophic wind. This latter condition is brought about by the presence of a warm low-pressure system (or cold high-pressure system). Because these nocturnal jet winds pose an ever-present threat to fire management activities in high mountainous areas, forecasting techniques should be developed.

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Supports the contention that the well-documented windspeed increase on high mountain slopes at night is due to the occurrence of a low-level jet wind. Discusses various aspects of the meteorological situation most likely to produce these winds. Cites an example of a low-level jet wind that produced strong winds on a ridgetop fire at night.

KEYWORDS: nocturnal mountain winds, low-level jet, wind influence on fire, meteorology

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